NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20034

RUDDER FORCE AND MOMENT MEASUREMENTS

ON A 1/4-SCALE SES 100 RUDDER

by

Douglas E. Layne

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SHIP PERFORMANCE DEPARTMENT

RESEARCH AND DEVELOPMENT REPORT

November 1973 Report 4118

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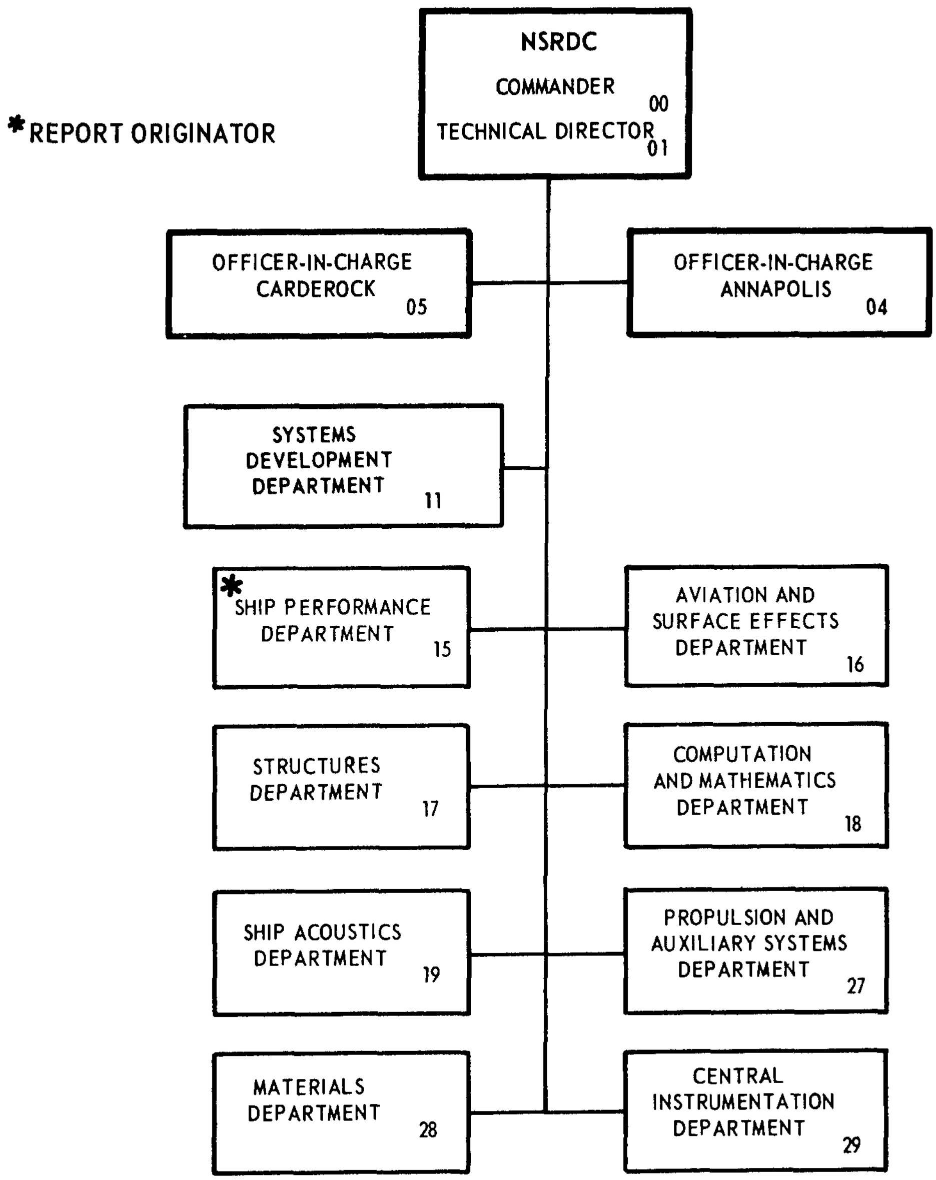

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DEPARTMENT OF THE NAVY
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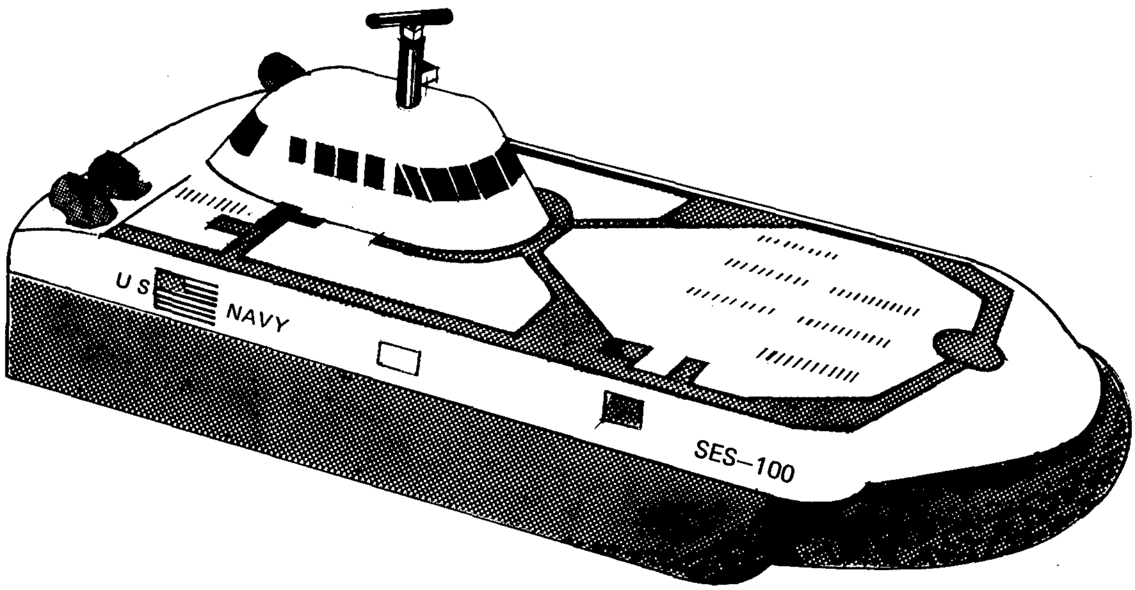
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NOTATION

A	Aspect ratio b^2/S
b	Span measured perpendicular to the plane of the root section, ft
$\overline{C}$	Mean geometric chord $(\text{Chord}_{tip} + \text{Chord}_{root})/2$
C_D	Drag coefficient $D/\frac{1}{2}\rho V^2 S$
C_L	Lift coefficient $L/\frac{1}{2}\rho V^2 S$
C_ℓ	Root bending moment coefficient about the intersection of the rudder stock with the rudder root chord $M_b/\frac{1}{2}\rho V^2 Sb$
$C_{M_{C/2}}$	Torque coefficient about the rudder stock $M_C/\frac{1}{2}\rho S\overline{C}V^2$
C_θ	Root pitching moment coefficient about the intersection of the rudder stock with the rudder root chord $M_\theta/\frac{1}{2}\rho V^2 Sb$
D	Drag parallel to flow
F_n	Froude number $V/\sqrt{g\ell}$
g	Acceleration due to gravity
L	Lift normal to direction of flow
M_C	Rudder stock torque about the rudder stock
M_b	Rudder bending moment about the intersection of the rudder stock with the rudder root chord
M_θ	Rudder pitching moment about the intersection of the rudder stock with the rudder root chord

P_s	Static pressure
P_v	Vapor pressure
R_e	Reynolds number $V\overline{C}/\nu$
S	Rudder planform area
V	Velocity of free stream
α	Rudder angle (angle of attack)
ν	Kinematic viscosity
ρ	Mass density
σ	Cavitation number $(P_s - P_v)/\frac{1}{2}\rho V^2$

ABSTRACT

Force and moment measurements were obtained in the NSRDC 36-in. variable-pressure water tunnel on a high-speed rudder with a geometric aspect ratio of 1.47. Data presented adhere to Froude scaling with an attempt to scale appropriate cavitation number. The cavitation index was varied from 3.4 to 0.16 for angles of attack of 0 to 29 deg. Lift, drag, and rudder stock torque were all significantly affected by variations in the cavitation number. Additional data are presented for Froude scaling only without considering the effect of cavitation number. The report also indicates a decrease in forces and moments with ventilation of the rudder at the trailing edge versus no ventilation.

ADMINISTRATIVE INFORMATION

The Naval Ship Research and Development Center (NSRDC) was requested by the Surface Effect Ship Program Office (SESPO) to construct a 1/4-scale model of a rudder designed for the SES-100 test craft and to conduct force and moment measurements. This work was funded under SESPO Project PM-17, Task Area S4229, NSRDC Work Unit 1556-022.

INTRODUCTION

Predictions of rudder forces and moments are required to determine rudder stock bearing loads for the SES test craft. The limits of the bearing loads in turn restrict the rudder angle of attack. The limitation on the angle of attack has the effect of decreasing the allowable angle with increase in speed. The requested evaluations were to include force and moment measurements for conditions comparable to full scale. The conditions were to be simulated through use of corresponding cavitation indices and Froude scaling.

METHOD AND PROCEDURES

The rudder was a 1/4-scale model of one designed for use with the SES-100 test craft. It was constructed of 17-4PH steel with a 4.5 in.-long shaft located 4.125 in. from the trailing edge. In turn, the rudder shaft was connected by a coupling to the strain dynamometer and lift and drag gages. The geometric aspect ratio was 1.47 with a projected area of 57.6 in.

The rudder profile is presented in Figure 1 together with typical section shapes. Lift, drag, and moments were measured on the rudder over a wide range of angles and cavitation indices.

The experiment was conducted in the NSRDC 36-in. variable-pressure water tunnel at water velocities from 25 to 59 ft/sec (corresponding to Reynolds numbers of 1.35×10^6 to 3.18×10^6), cavitation indices of 0.16 to 3.4, and angles of attack from 0 to 29 deg. The variations in velocity yielded the corresponding values to achieve Froude scaling. Pressure in the tunnel was also varied to give cavitation indices that corresponded to full scale. In effect, two separate evaluations were conducted:

1. Condition I considered both Froude and cavitation scaling under conditions of external venting and no venting. Cavitation number scaling was used in order to simulate the full-scale cavitation number. An explanation of this method of scaling has been given by Coder.[1]

2. Condition II consisted of Froude scaling only, and pressure was maintained close to atmospheric in the test section.

Table 1 gives the conditions under which the experiments were conducted.

TABLE 1 - EVALUATION CONDITIONS

Full Scale		Condition I		Condition II	
Velocity knots	Cavitation Number	Velocity knots	Cavitation Number	Velocity knots	Cavitation Number
30	0.832	15	0.85	15	3.4
40	0.468	20	0.49	20	1.9
50	0.300	25	0.30	25	1.2
60	0.208	30	0.21	30	0.86
70	0.153	35	0.16	35	0.63

[1] Coder, D. W. et al., "Hydrodynamic Design and Testing of HYSURCH Sensor Body," NSRDC Report 3304, pp. 28-30 (Apr 1970).

Air content in the tunnel was maintained approximately at 10-percent saturation at a temperature of 75 F and atmospheric pressure. The 10-percent air content provided better photographic conditions at low pressures than higher air contents.

The rudder was evaluated below an 8- × 21.5-in. aluminum plate with a gap of $0.04\overline{C}$ between the top of the rudder and the plate. The rudder and plate were positioned to give a pitch angle of -1 deg. Forces and moments were measured with four 2-in. modular force gages and a strain gage dynamometer mounted on the rudder stock between the locations of the force gages. Lift and drag forces are accurate to ±0.5 lb, rudder stock bending moments (hinge moments) to ±1.0 in.-lb, and pitch moments to ±1.0 in.-lb. Lift forces on the model rudders varied from 0 to 320 lb while the drag varied from near zero to 180 lb. Maximum rudder stock torques were in the order of 250 in.-lb.

Figure 2 presents directions of positive forces and moments. The moments shown are given at the intersection of the rudder stock with the rudder base. The rudder is shown with a positive yaw angle or yaw to port. A positive torque coefficient means that a force must be applied to the rudder stock to decrease the angle of attack shown in Figure 2. The figure also shows the trough at the trailing edge used in ventilating the rudder.

The measurements were taken with and without forced ventilation, i.e., injection of air into the flow at the trailing edge of the rudder. Since it was not physically possible to scale the ventilation injection pressure, ventilation supply pressure values were set at atmospheric for Condition I and at 15 psig for Condition II. Preliminary experiments had indicated very little difference (within test accuracy) in forces as ventilation pressure varied from 10 to 40 psig.

The data acquisition system (Figure 3) consisted of carrier amplifiers and a scanner coupled to an Interdata Model 70 computer with a Kennedy tape deck and a high-speed printer for the output device. The data acquisition system was capable of taking approximately 1000 samples of data per channel. These samples were averaged and analyzed to give the output in coefficient form. All data were reduced to nondimensional coefficient form.

RESULTS AND DISCUSSION

Two sets of evaluation data are presented for the different approaches. Figure 4-7 show lift, drag, torque, bending moment, and pitching moment data for Condition I (Froude and cavitation number scaling); the curves pertain to the "no ventilation" condition. Figures 8-11 present comparable data for Condition II (Froude scaling only and ventilation). Velocities indicated on these graphs are full scale.

Data from the curves for Froude scaling only (Figures 8-11) gave markedly different values from those obtained when both Froude and cavitation number scaling were considered (Figures 4-7). This difference was particularly evident in the measurements for drag and torque. For example, compare the sudden change in drag at 50 knots for Condition II (Figure 9) to that for Condition I (Figure 5). The torque coefficient in Figures 6 and 10 showed a change in sign as the yaw angle increased, indicating a forward movement of the center of pressure. Although this may be good from a loading viewpoint, it could create problems in control as the torque goes from positive to negative, in other words as the center of pressure moves from aft to forward of the rudder stock.

A comparison of the effect of Froude scaling only versus Froude and cavitation number scaling is presented in Figure 12 for lift data taken during ventilation of the rudder trailing edge. These curves are intended to represent the differences that occurred during Conditions I and II. Each combination yielded a different prediction. For example, taking a base condition of, say, 30 knots with the corresponding cavitation number of 0.85, the values indicated by the closed circles were obtained when Froude and cavitation number scaling was maintained. Values obtained when only Froude scaling was considered are indicated by the open circles. Values obtained if only cavitation number scaling is considered are denoted by triangles.

Ventilation of the rudder at the trailing edge caused little difference in the coefficients. The difference was insignificant at angles less than 10 deg although the tendency for ventilation to decrease the forces was present for all forces measured. As the ventilation was increased, the effect of the forced ventilation seemed to be lessened at angles above 10 deg. Figure 4 shows as much as a 15-percent decrease in lift due to

ventilation at 30 knots, but the decrease amounted to only 6 percent at 40 knots and 2 percent at 50 knots.

Photographs of the model under Condition I are presented in Figures 13-16 for both ventilation and no ventilation at various angles of attack and simulated full-scale velocities of 30, 40, 50, and 60 and 70 knots. Photographs of the model under Condition II with ventilation only are shown in Figures 17-20 at various angles of attack and the same simulated full-scale velocities.

The photographs give a good indication of the magnitude of cavitation at various angles of attack. As a general rule, ventilation of the trailing edge had little effect on the leading edge until cavitation occurred at the leading edge, at which time the ventilation did extend the size of the cavity. This was again noted primarily at the lower velocities, e.g., Figure 14. As velocity was increased, the effect of ventilation was less noticeable as indicated in Figures 14-16. Some unsteady flow was noted at the trailing edge of the rudder, for example, at 7 deg in Figure 17 and at -5.5 deg in Figure 18.

As expected, the photographs for Condition II showed different cavitation patterns and also a lesser degree of cavitation than that in Condition I. Compare the various photographs for the ventilation condition only. One indication of the physical difference in the two approaches to scaling is the visible presence of the tip vortex in Figures 15 and 16 and the apparent lack of a tip vortex in the corresponding figures for Froude scaling only (Figures 19 and 20).

It is generally considered that data obtained by adhering to Froude and cavitation number scaling give a better indication of full-scale conditions than do data from only Froude scaling at atmospheric pressure. The present data tend to bear this out.

Drag, torque, lift, and bending moment measurements for Condition I (Froude and cavitation number scaling) are compared in Figures 21 and 22 to similar data obtained by Gregory and Dobay[2] on high-speed rudders. The

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[2]Gregory, D. L. and G. F. Dobay, "The Performance of High-Speed Rudders in Cavitating Environment," SNAME Spring Meeting, Lake Buena Vista, Florida (2-4 Apr 1973).

comparison data in these figures pertains to a rudder with a geometric aspect ratio of 1.5 and a thickness to chord ratio of 0.11. Rudder 3 of the Gregory report is approximately the same as the SES rudder, but the investigation was conducted in a different facility and at a higher air content. The SES evaluation required a different facility because of the low pressures needed to obtain the proper cavitation numbers and because the required velocities exceeded the limits of the facility used by Gregory. The Gregory-Dobay data for torque coefficient have been transposed to the SES rudder stock, and their sign convention[2] changed in order to achieve consistency. There was good agreement for Rudder 3 of the Gregory-Dobay data[2] and Condition I data of the present investigation.

CONCLUSIONS

1. Both Froude and cavitation number scaling effects must be considered in order to provide meaningful predictions of full-scale performance from rudder model data.

2. Ventilation of the rudder had little effect on lift and drag at velocities greater than 50 knots.

3. Ventilation tended to extend the rudder cavity when cavitation was present.

4. The movement of the center of pressure of the rudder stock from aft to forward could present serious problems in control inasmuch as this causes a reverse in the torque. This movement occurred from 10- to 15-deg angles of attack at speeds of 30 and 40 knots.

5. There was good agreement between the present data and a previous evaluation of a similar rudder.

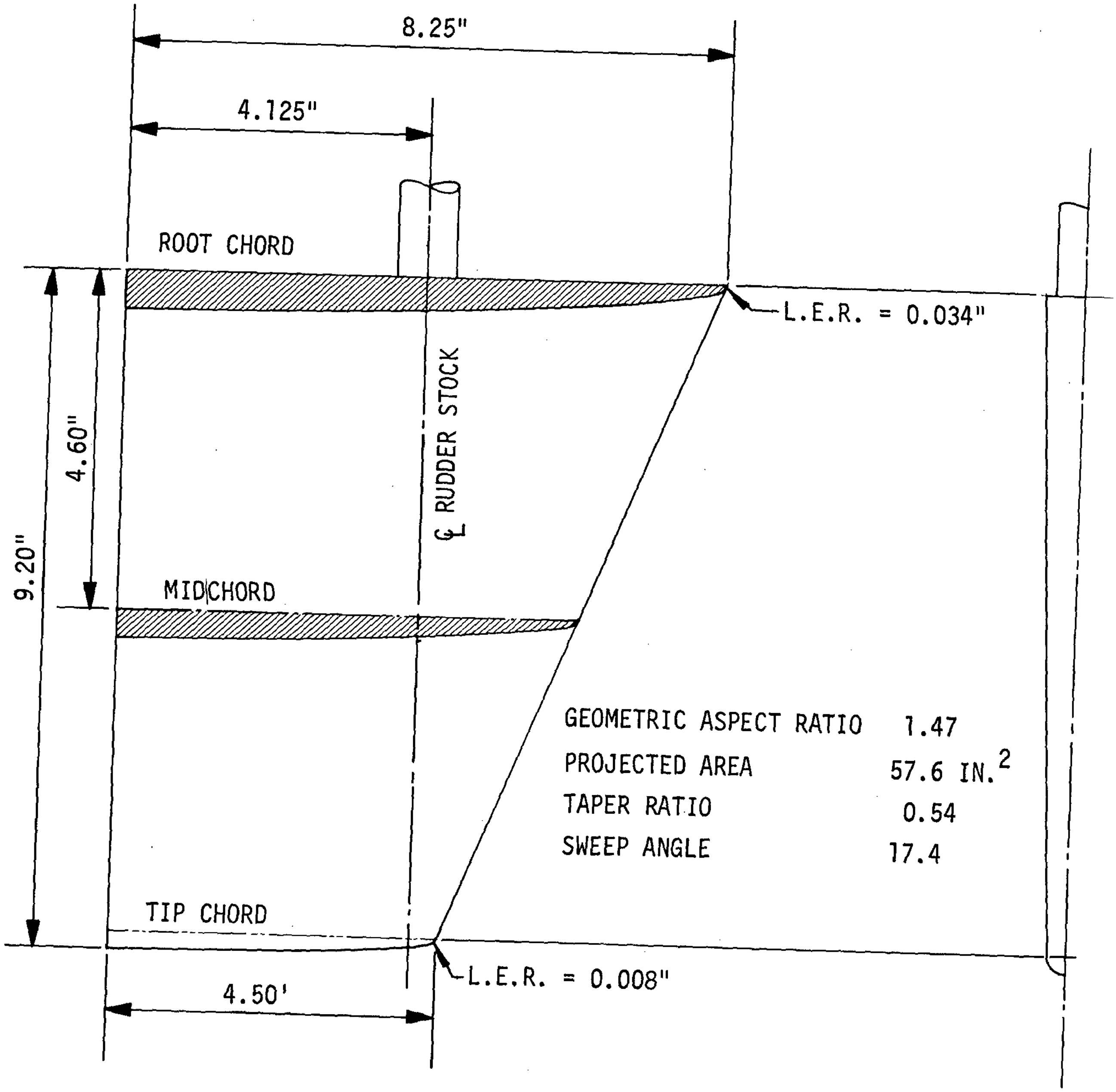


Figure 1 - Rudder Profile and Section Shapes

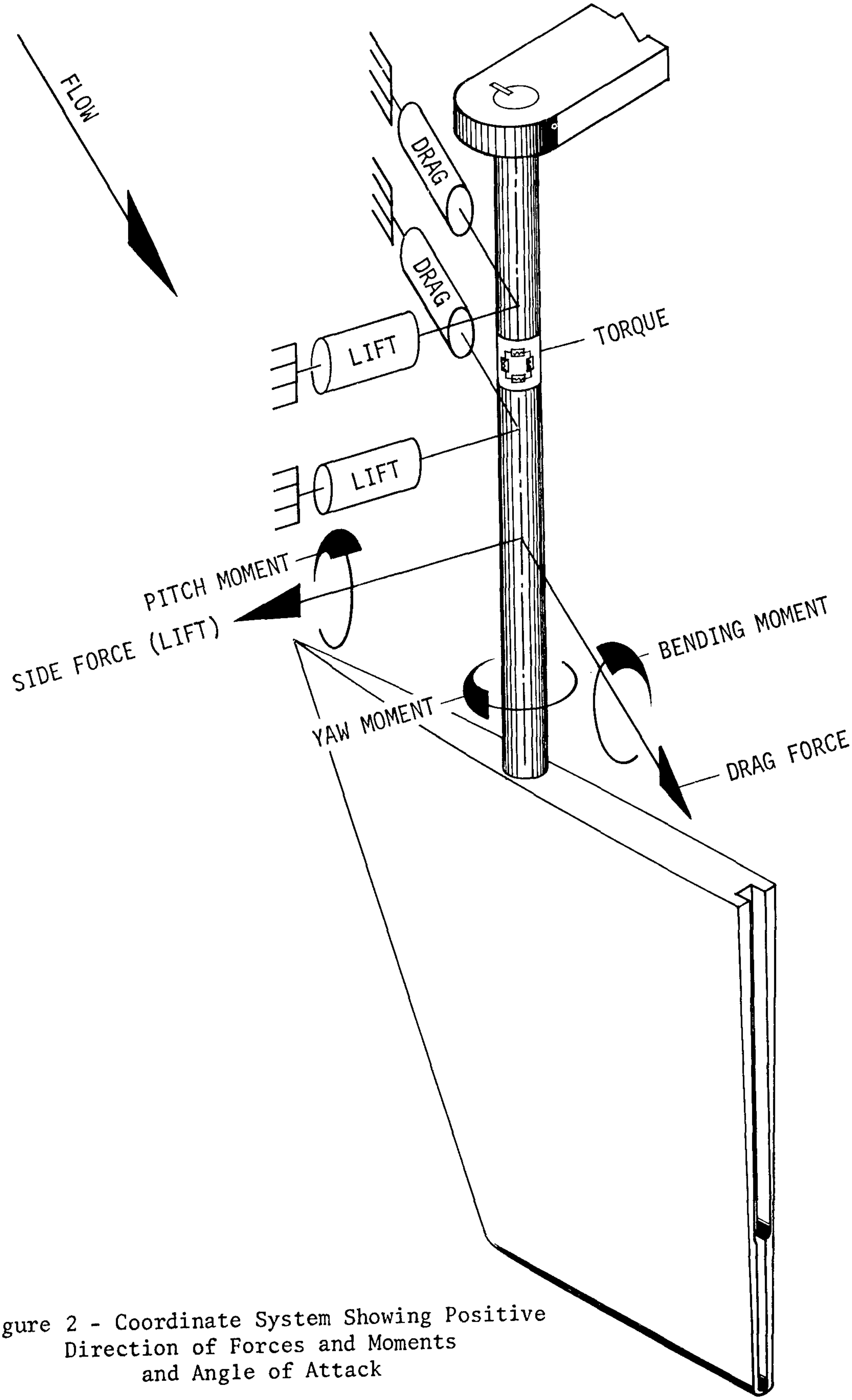
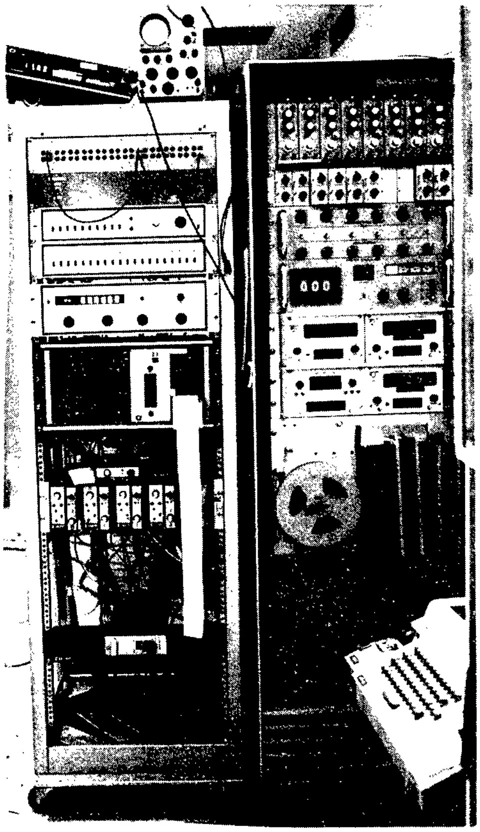
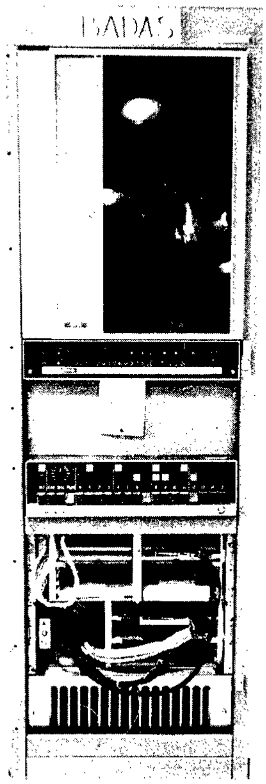


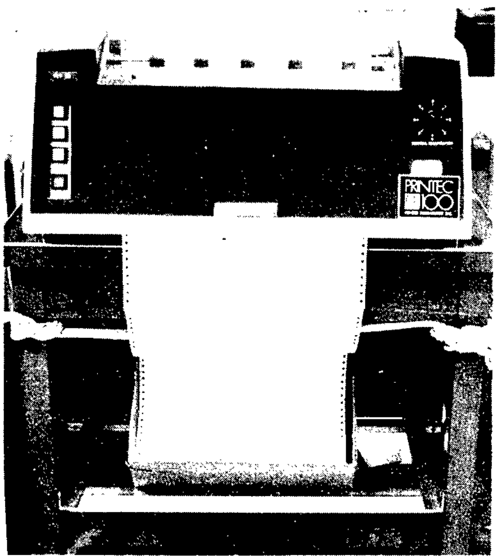
Figure 2 - Coordinate System Showing Positive
Direction of Forces and Moments
and Angle of Attack



CARRIER AMPLIFIERS
AND SCANNER



INTERDATA MOD. 70,
KENNEDY TAPE



HIGH-SPEED PRINTER

Figure 3 - Data Acquisition System

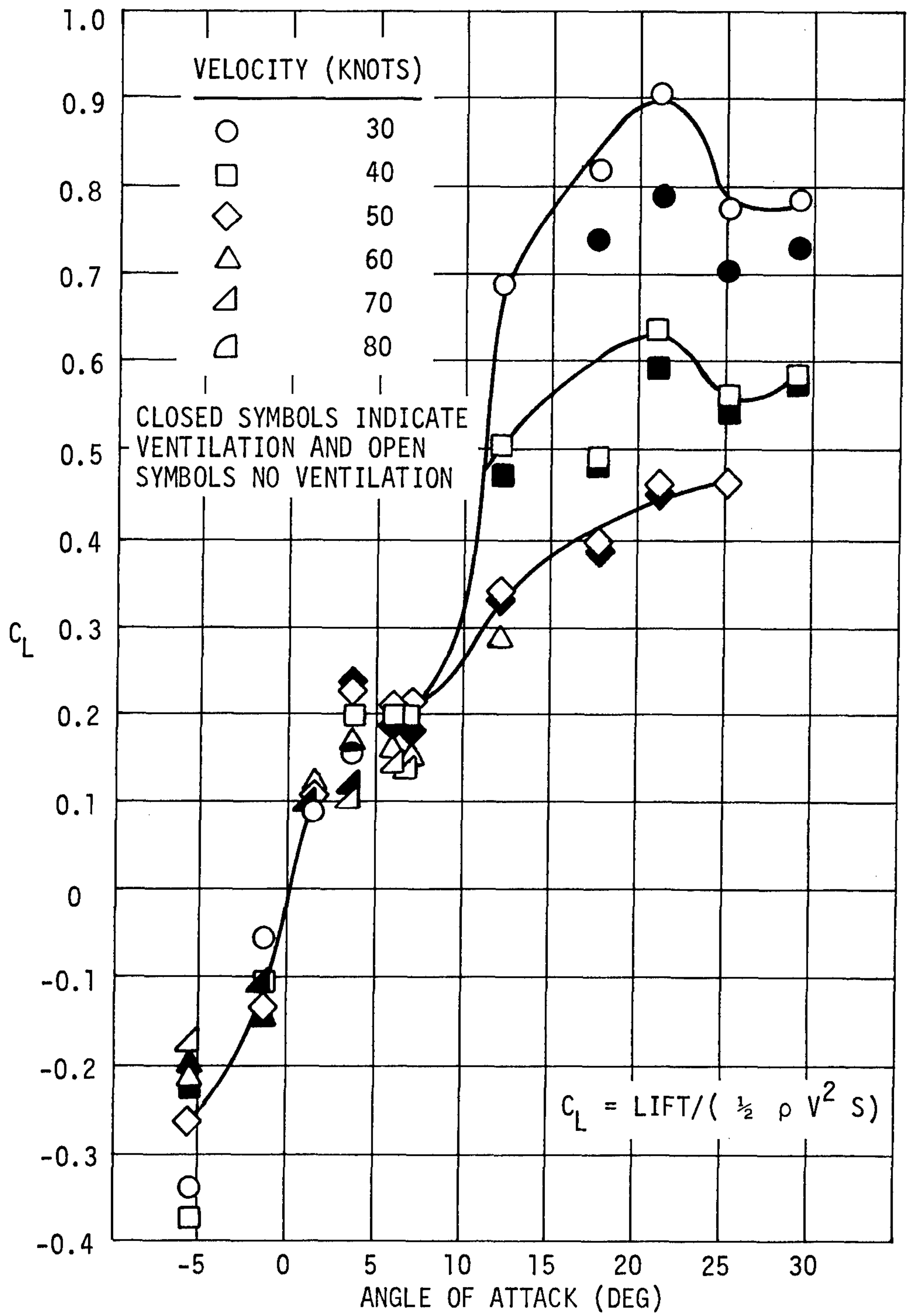


Figure 4 - Lift Coefficients versus Rudder Angle at Various Velocities Using Cavitation and Froude Scaling (Condition I)

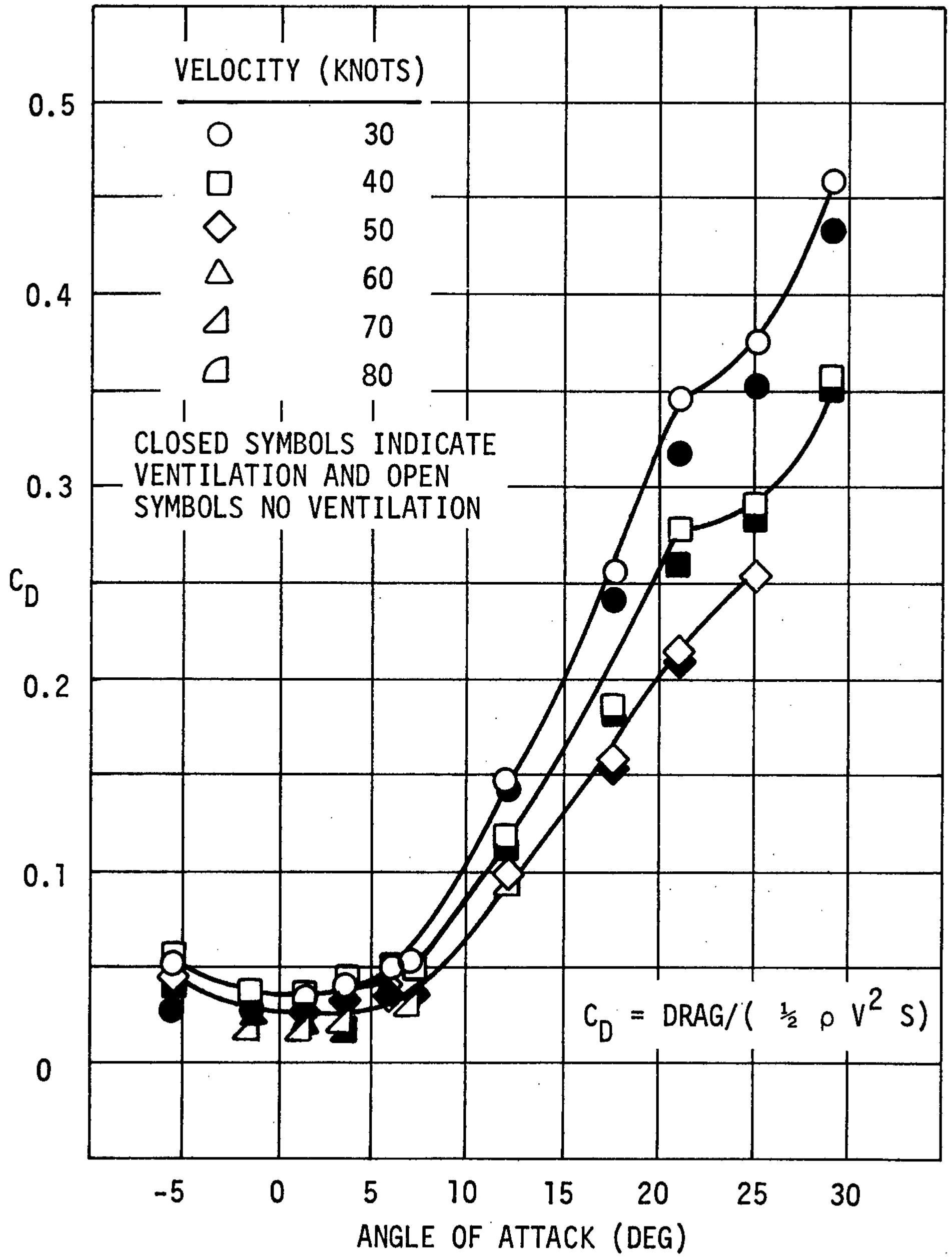


Figure 5 - Drag Coefficients versus Rudder Angle at Various Velocities Using Cavitation and Froude Scaling (Condition I)

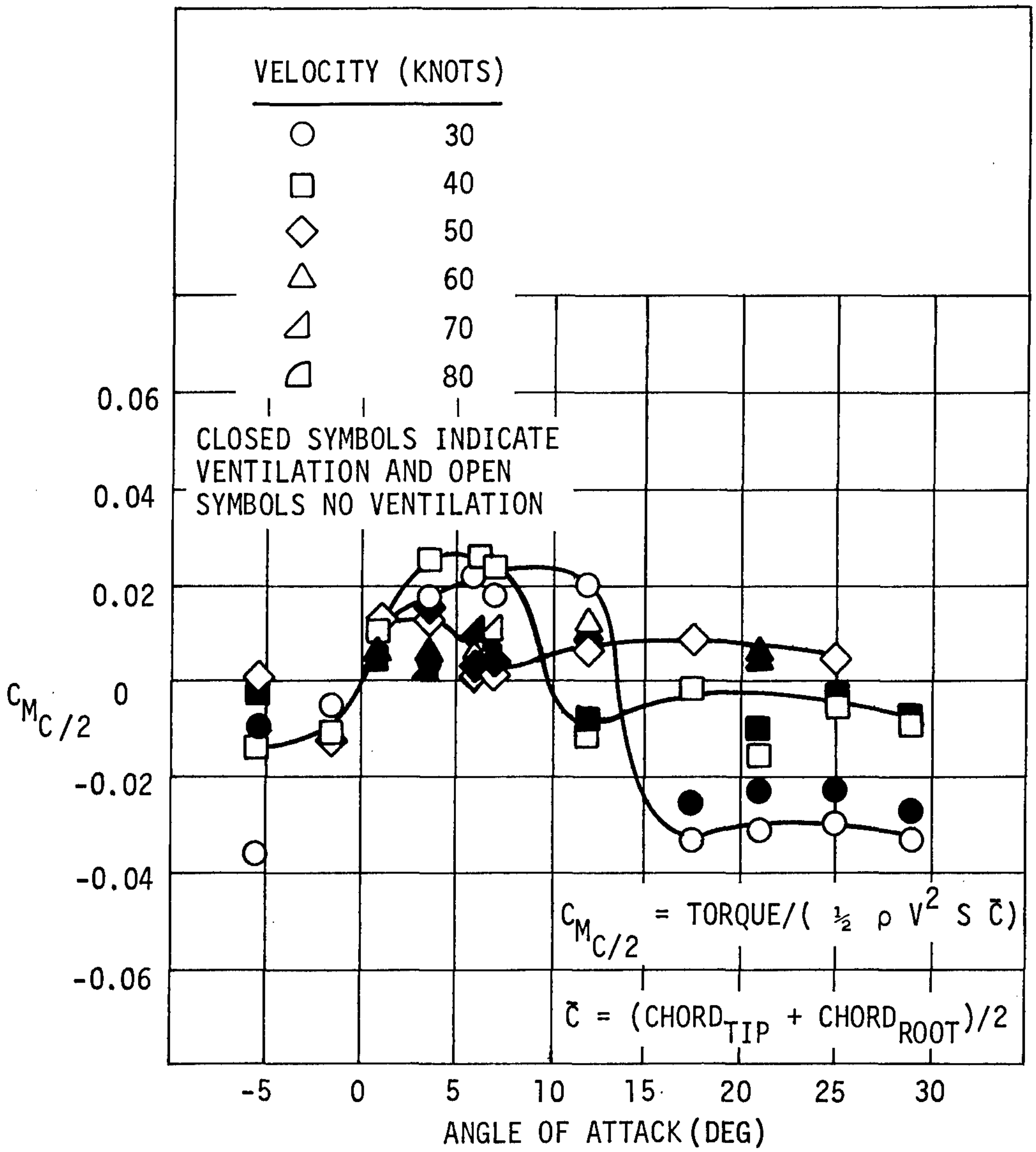


Figure 6 - Torque Cavitation Versus Rudder Angle at Various Velocities Using Cavitation and Froude Scaling (Condition I)

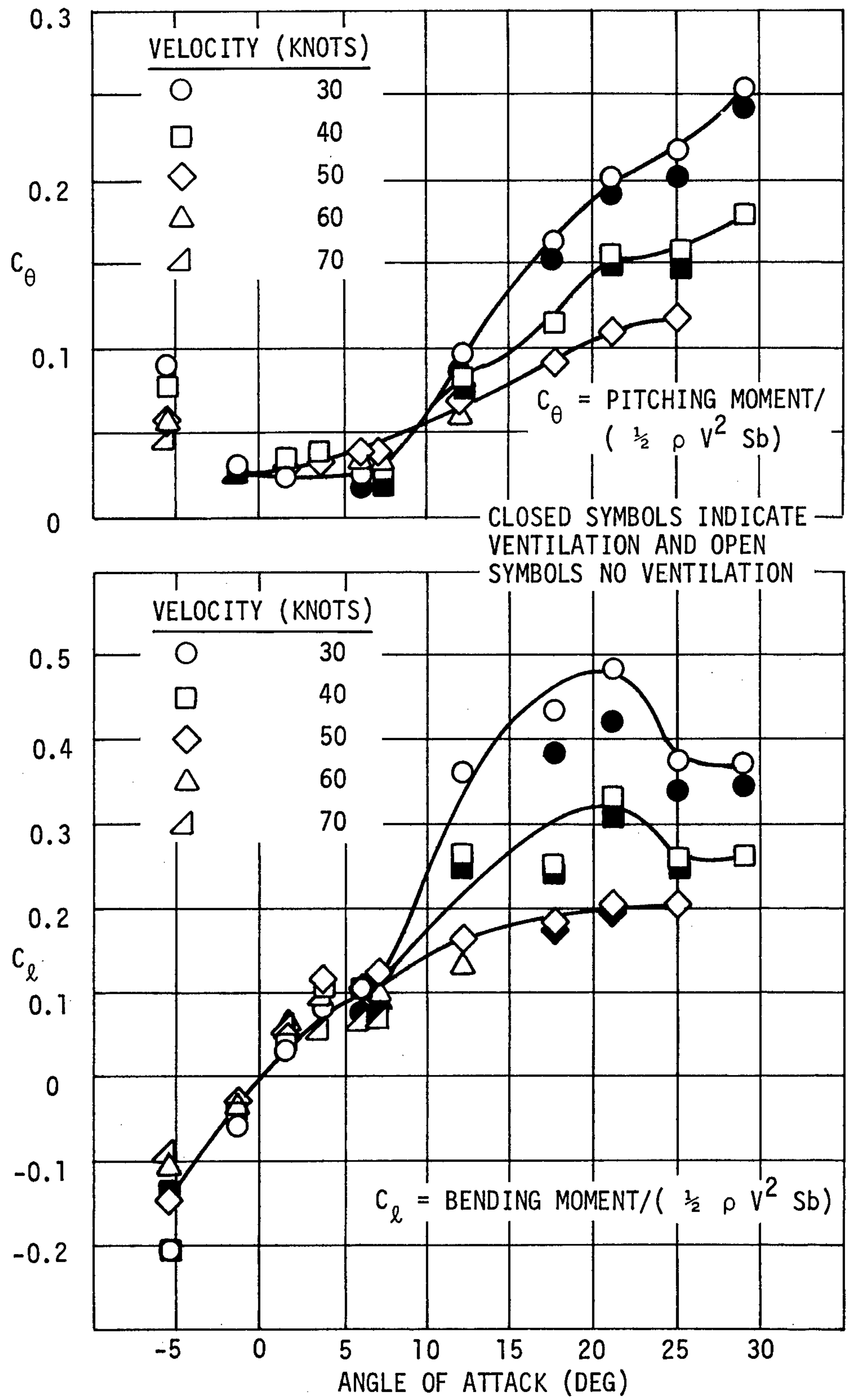


Figure 7 - Bending and Pitch Moment Coefficients versus Rudder Angle at Various Velocities Using Cavitation and Froude Scaling (Condition I)

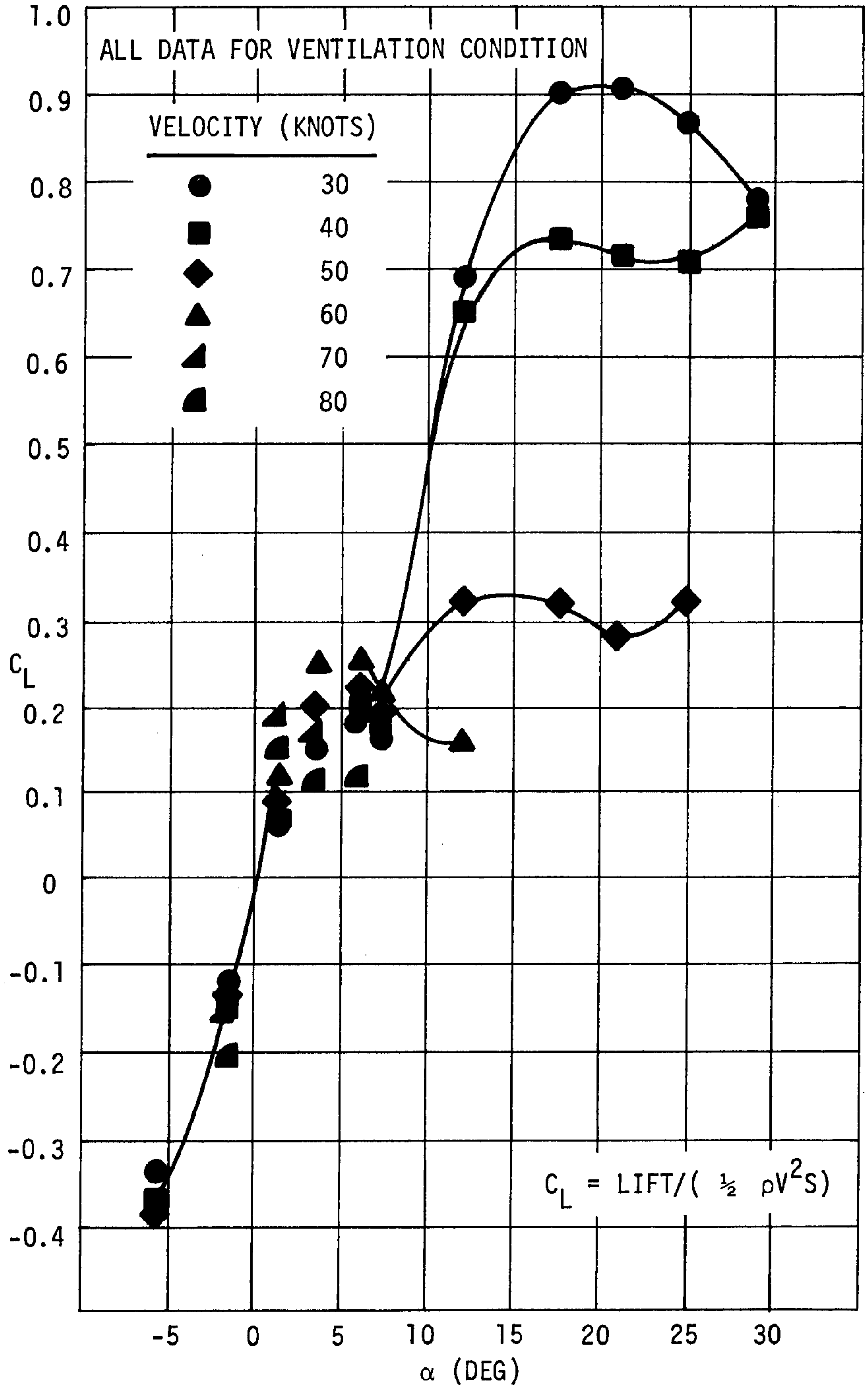


Figure 8 - Lift Coefficient versus Rudder Angle at Various Velocities Using Froude Scaling Only (Condition II)

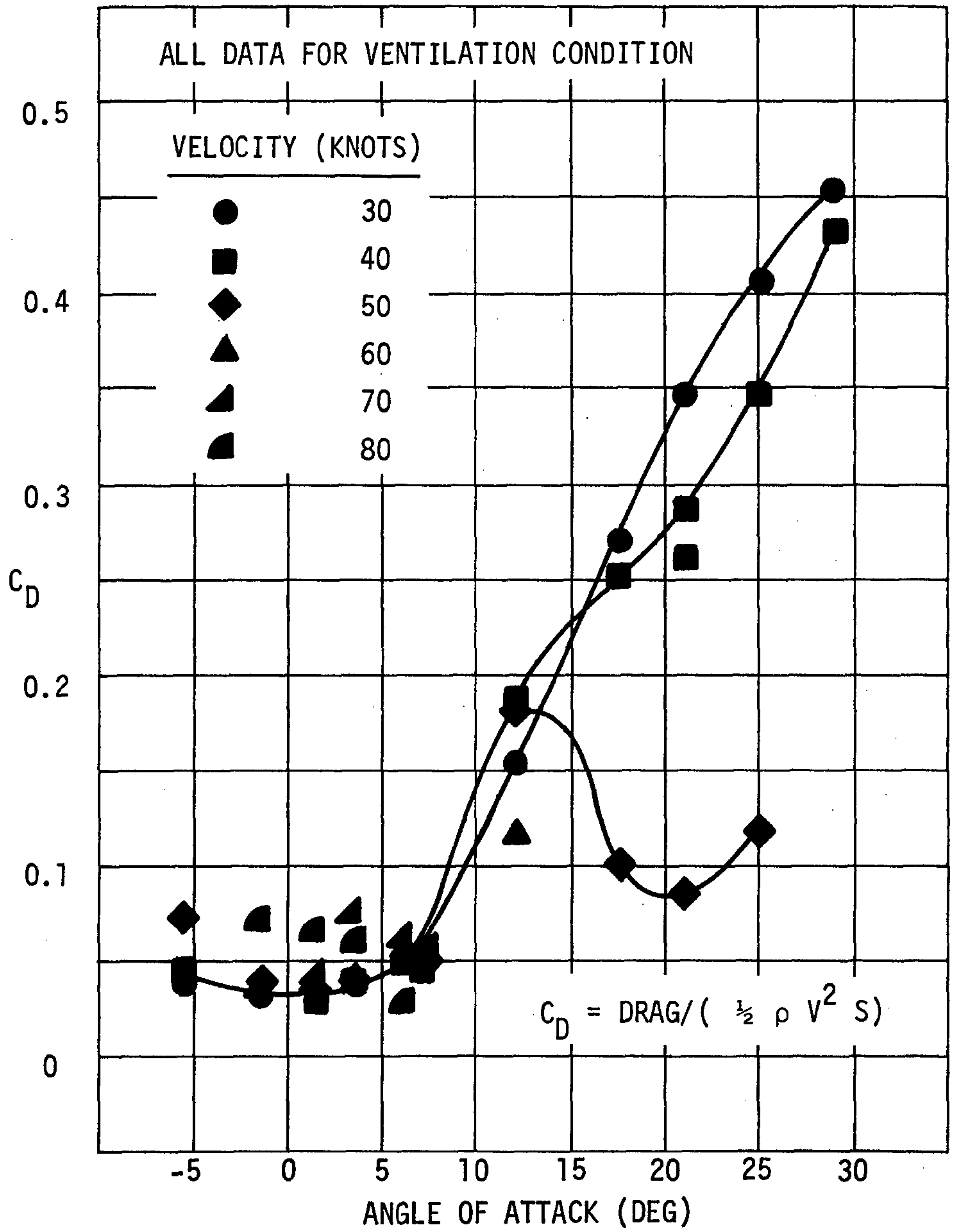


Figure 9 - Drag Coefficient versus Rudder Angle at Various Velocities Using Froude Scaling Only (Condition II)

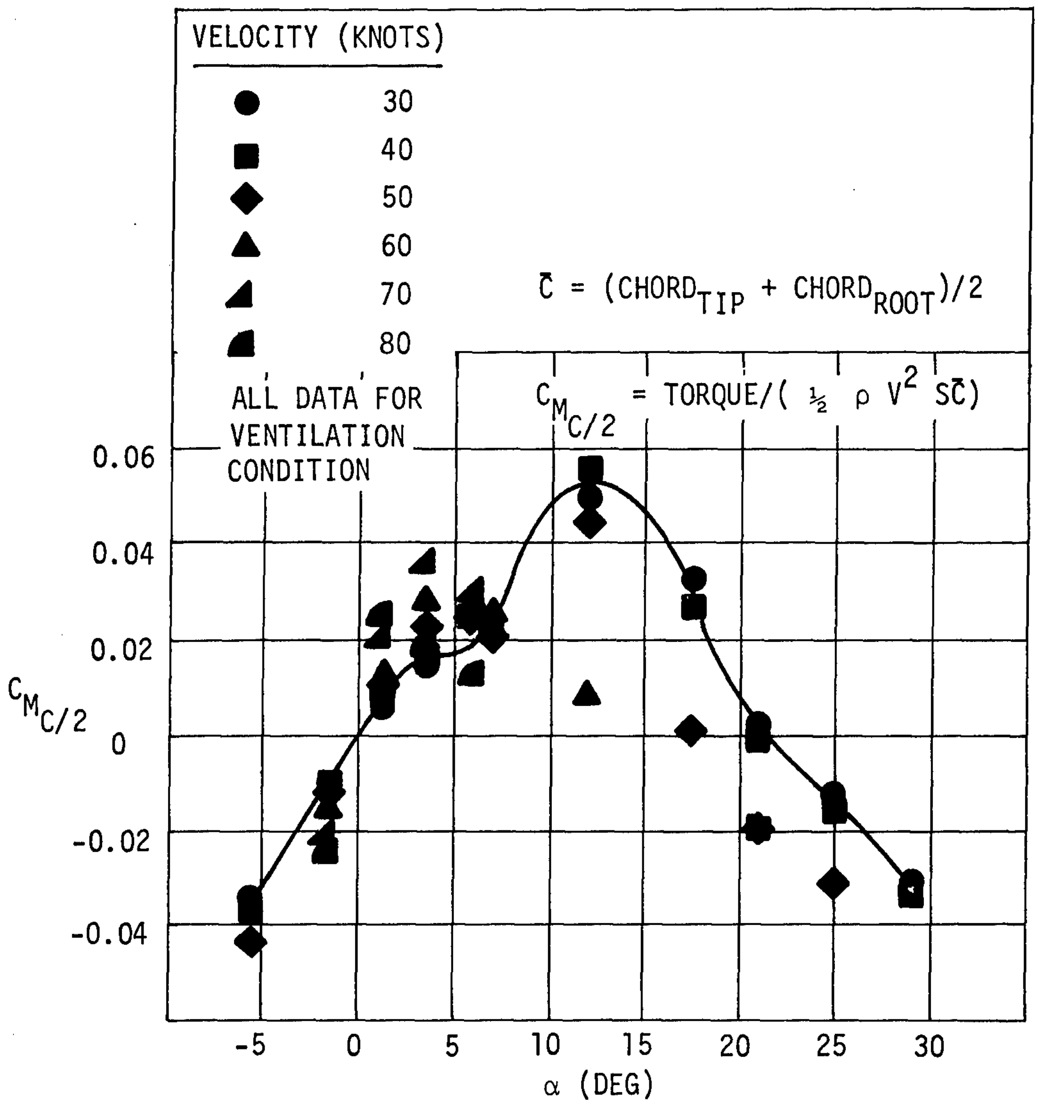


Figure 10 - Torque Coefficient Versus Rudder Angle at Various Velocities Using Froude Scaling Only (Condition II)

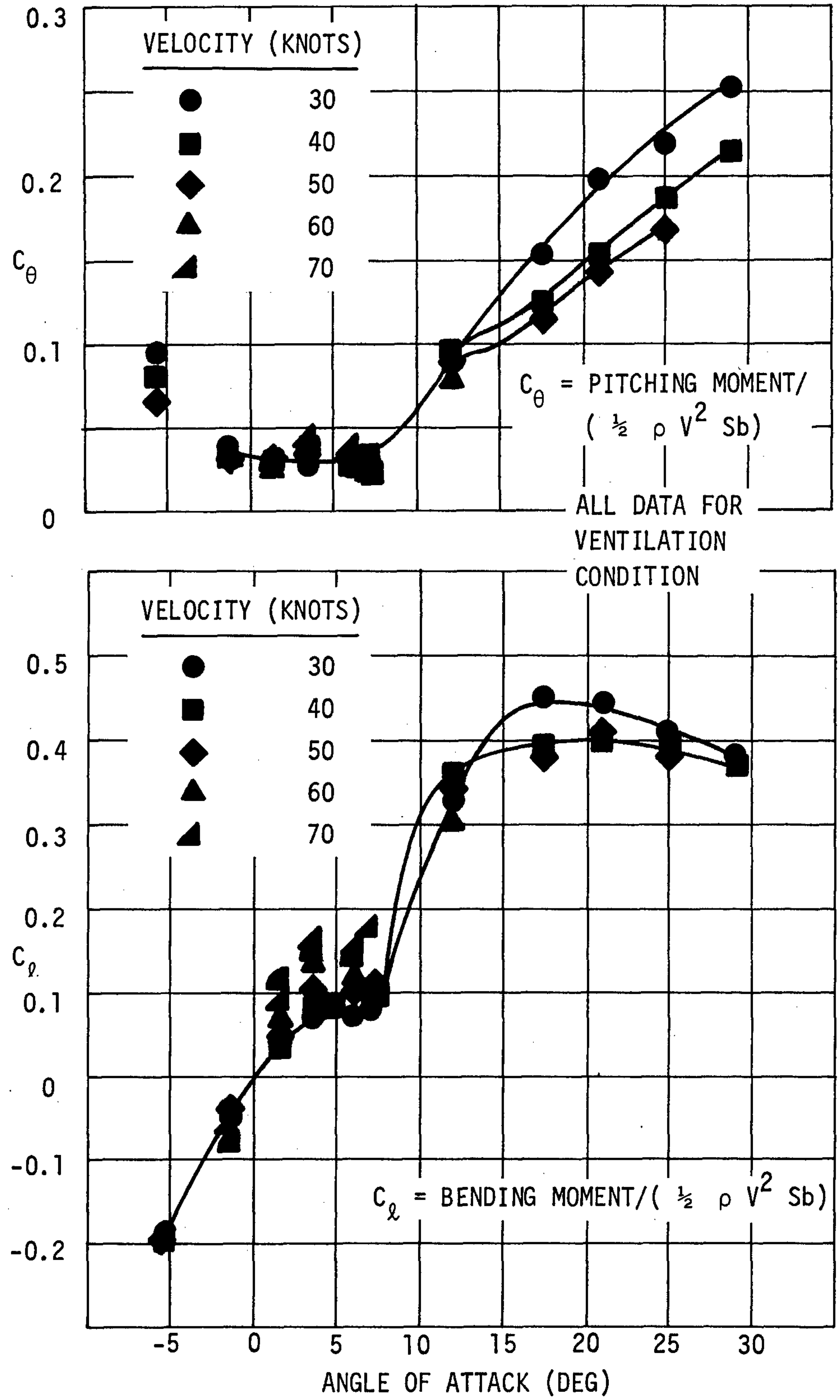


Figure 11 - Bending and Pitching Moment Coefficients versus Rudder Angle at Various Velocities Using Froude Scaling Only (Condition II)

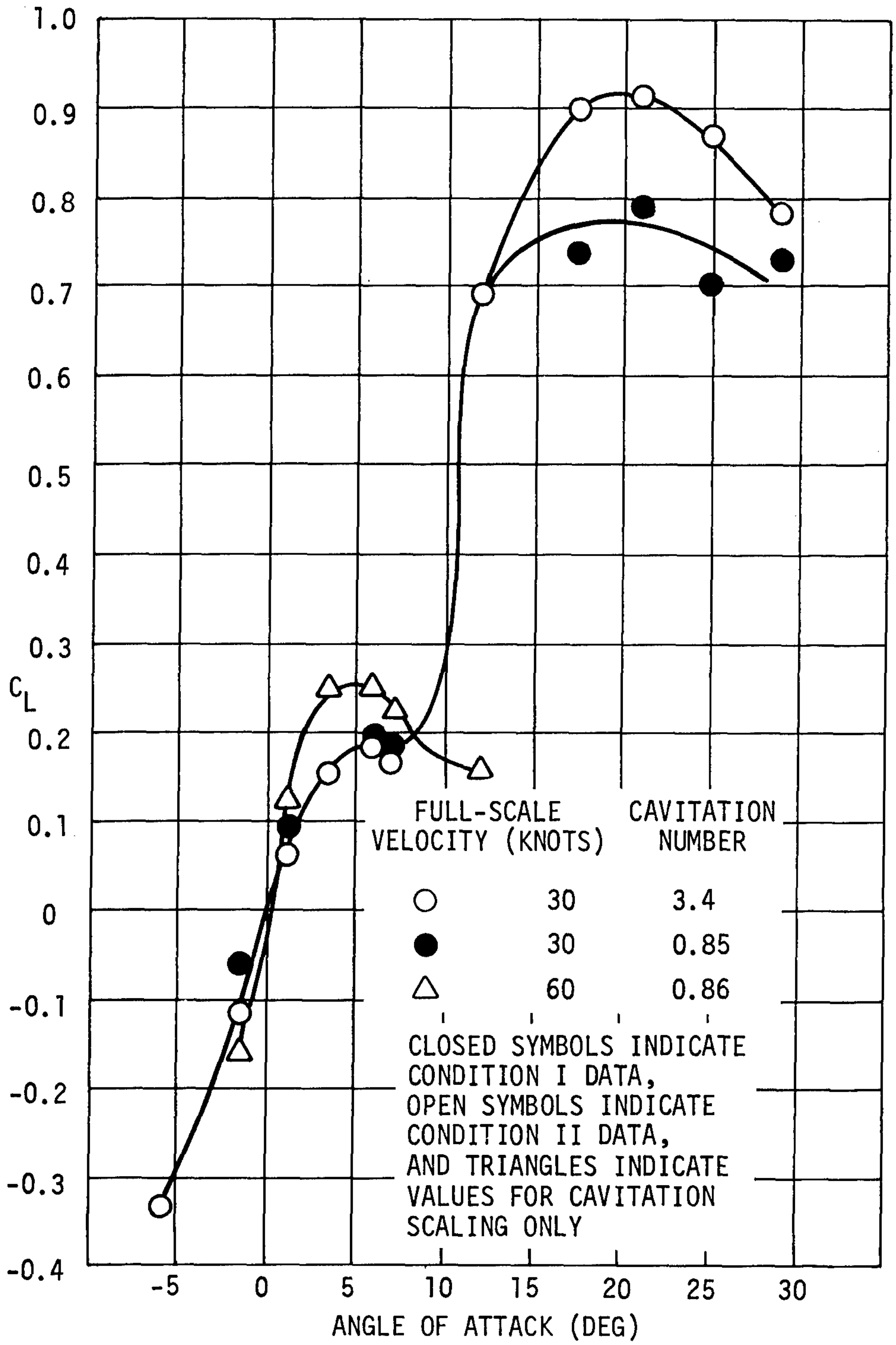


Figure 12 - Comparison of Lift Data Obtained under Conditions I and II

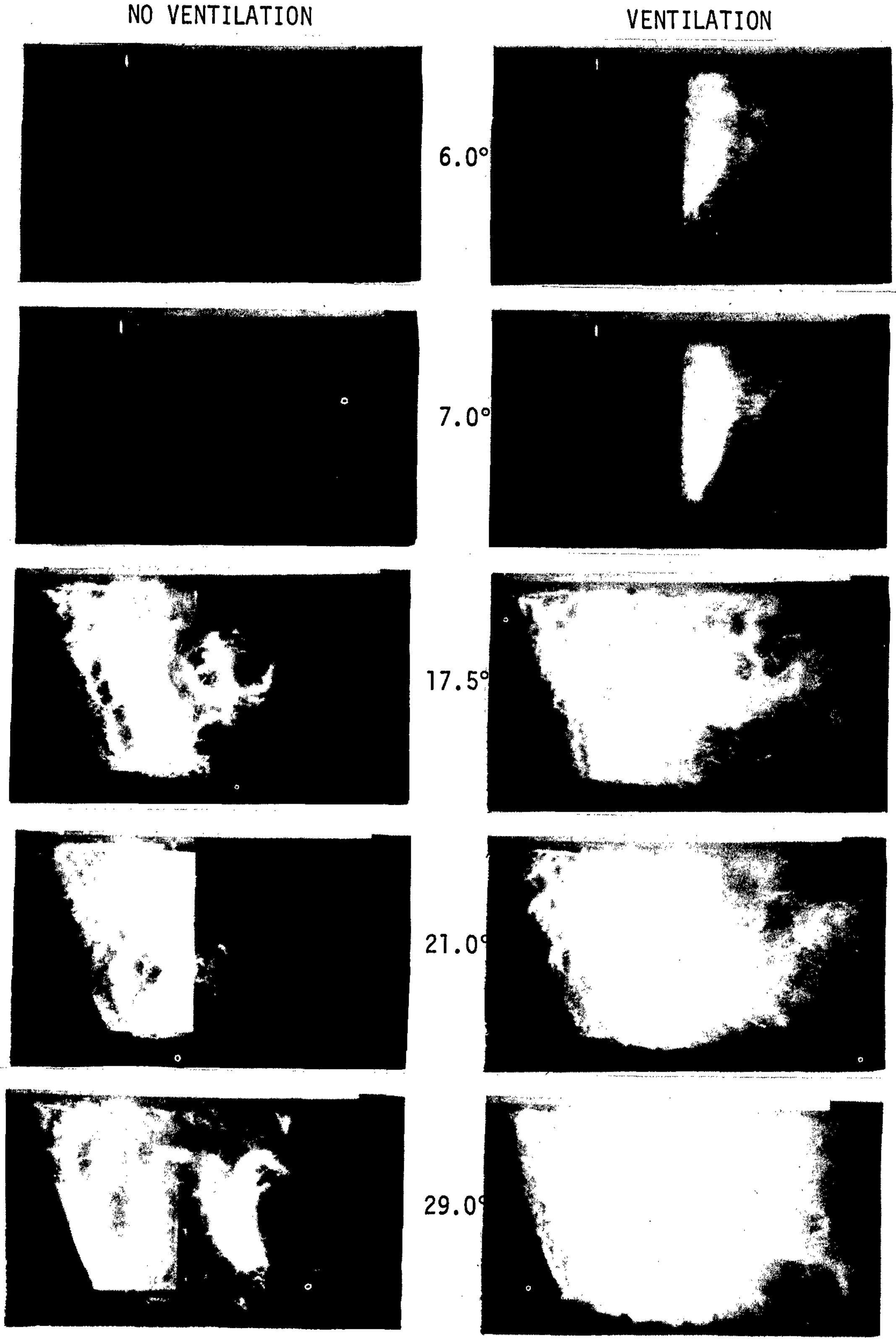


Figure 13 - Condition I Corresponding to 30 Knots Full Scale

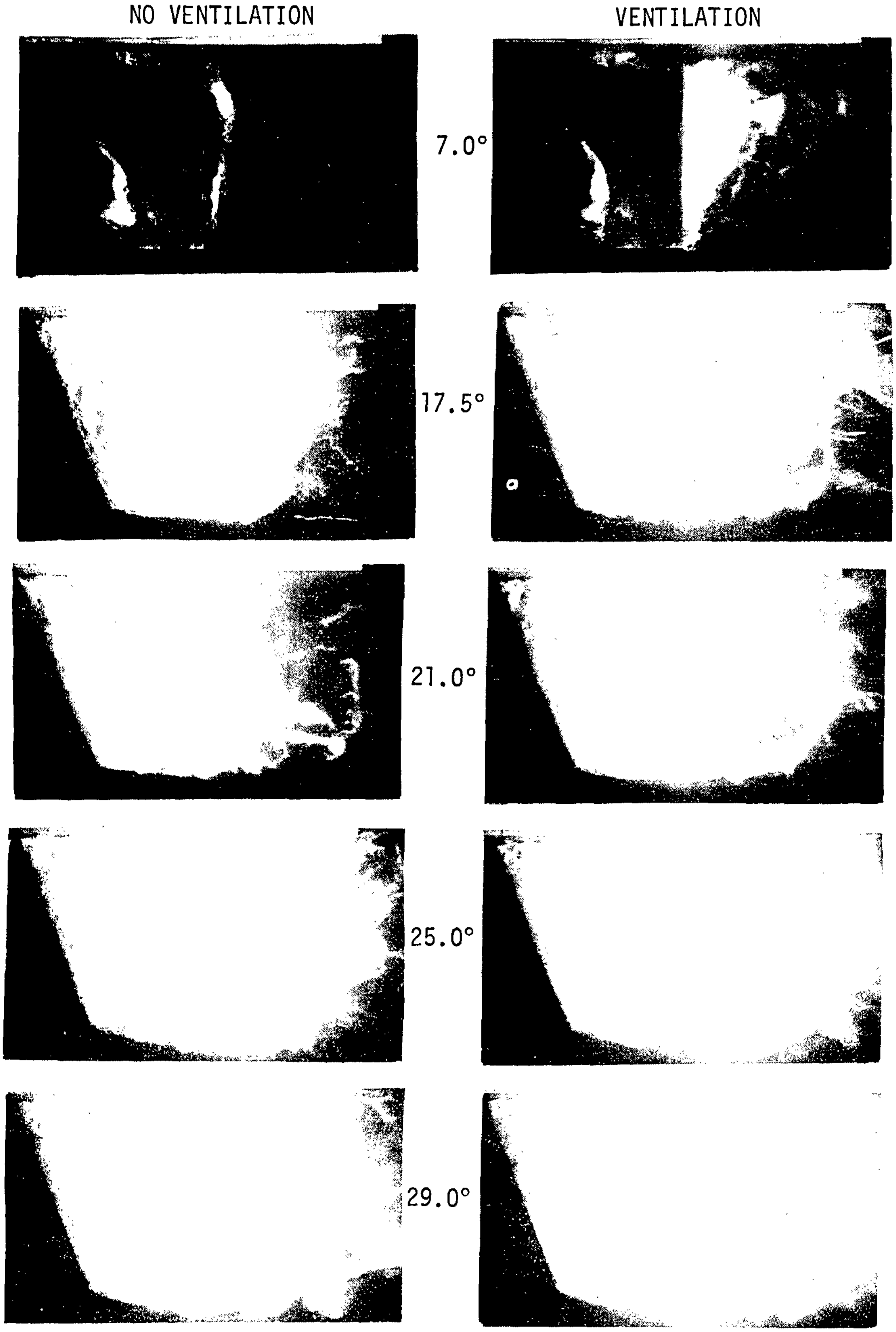


Figure 14 - Condition I Corresponding to 40 Knots Full Scale

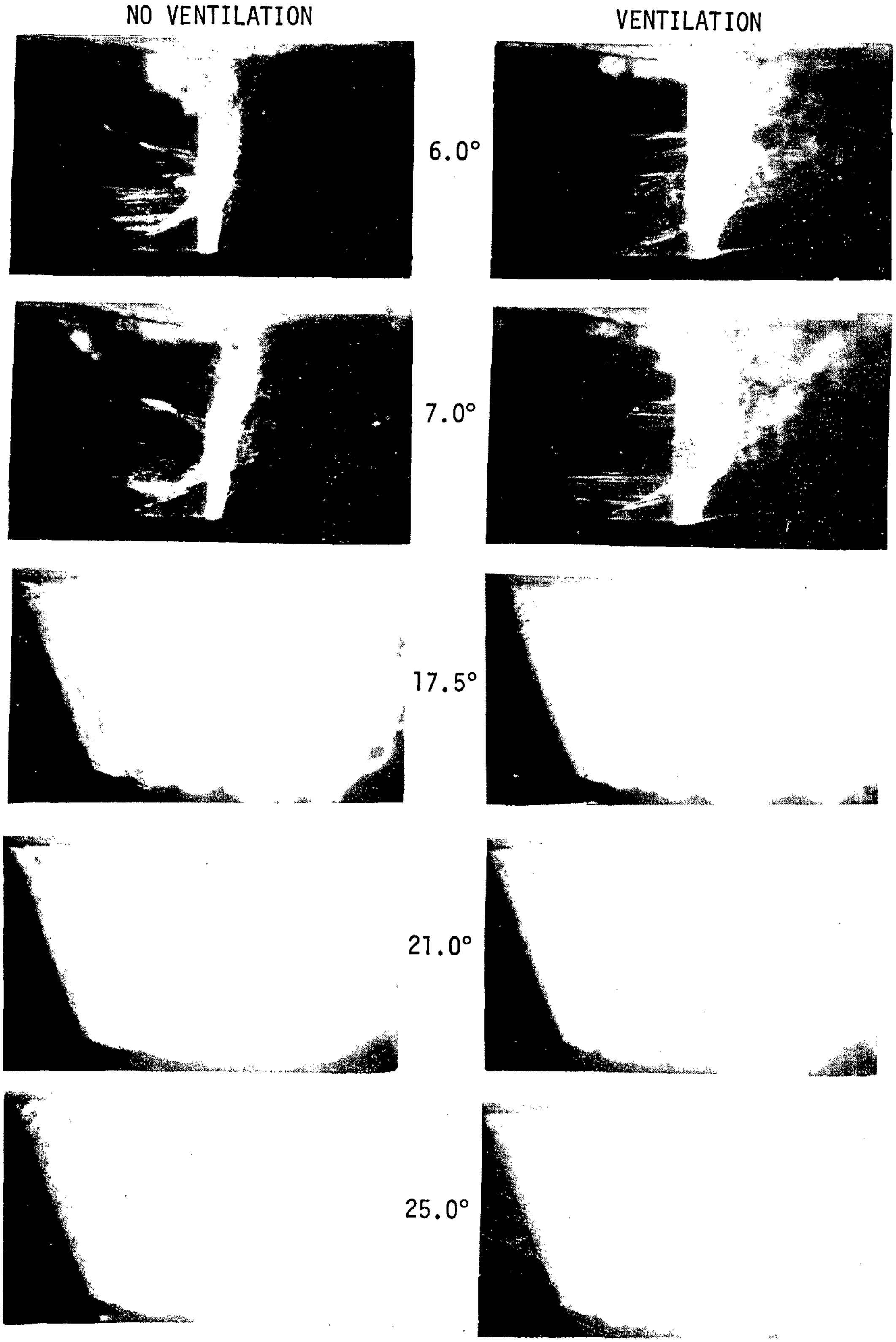


Figure 15 - Condition I Corresponding to 50 Knots Full Scale

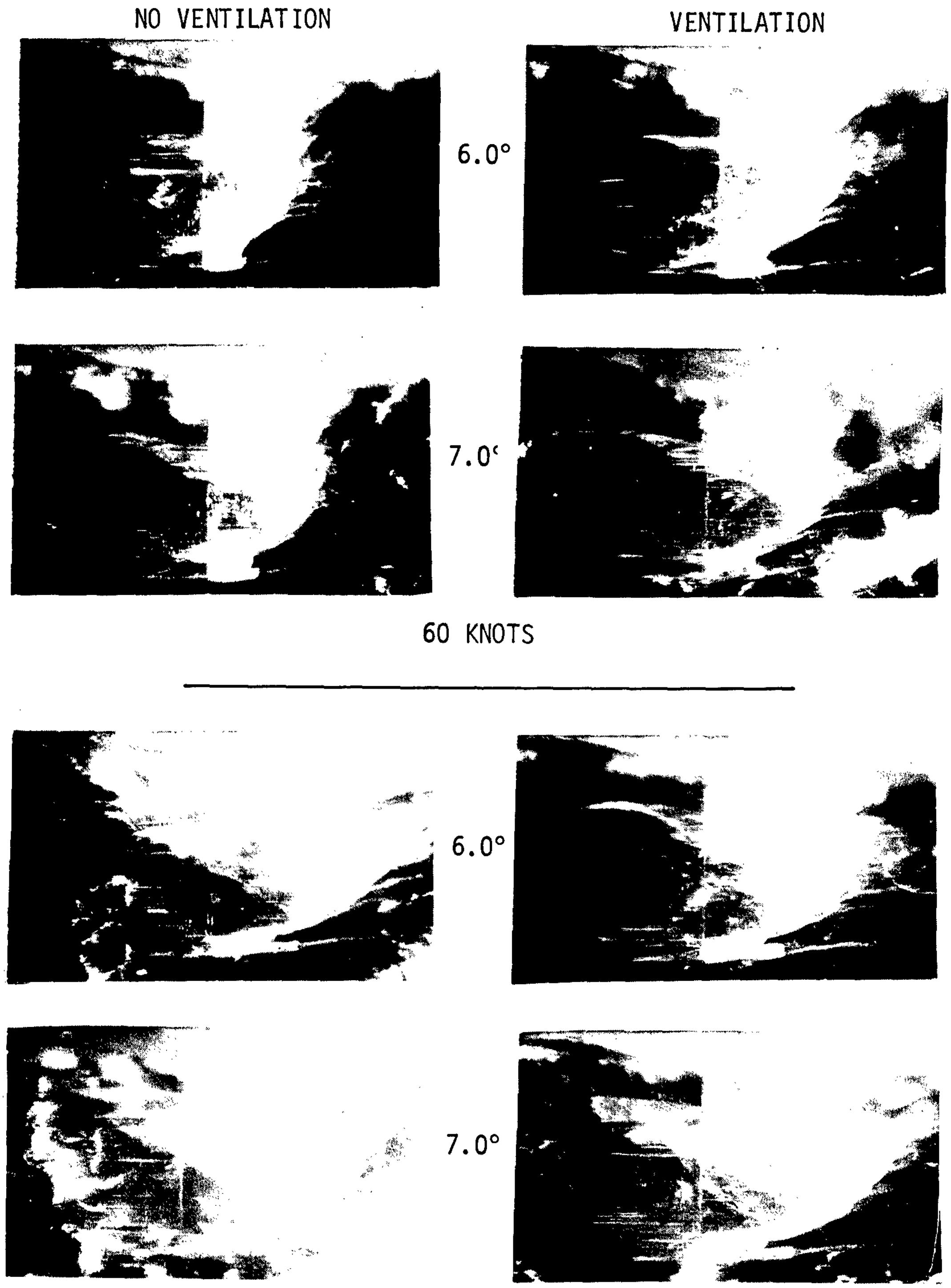
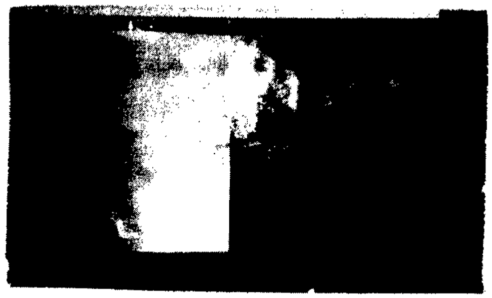


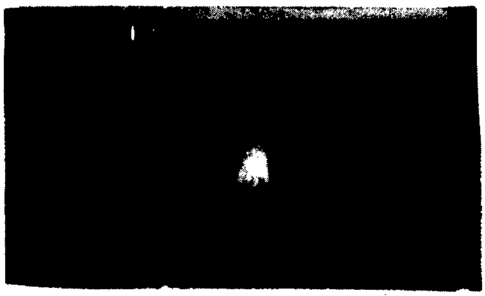
Figure 16 - Condition I Corresponding to 60 and 70 Knots Full Scale

VENTILATION

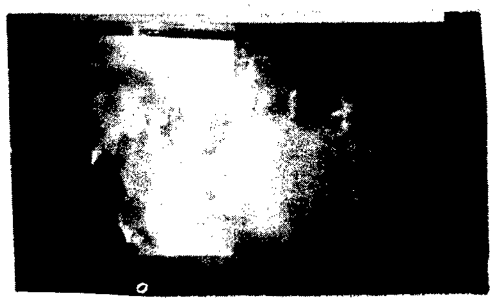
-5.5°



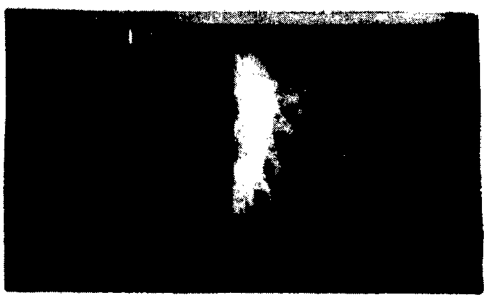
17.5°



6.0°



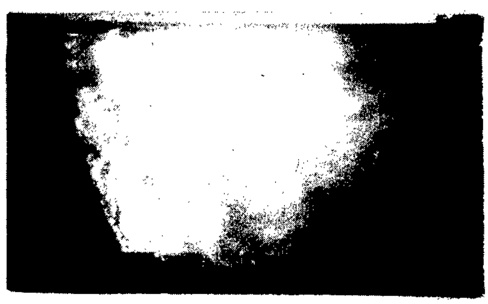
21.0°



7.0°

25.0°

12.5°



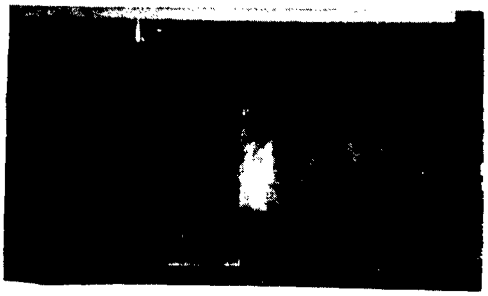
29.0°

Figure 17 - Condition II Corresponding to 30 Knots Full Scale

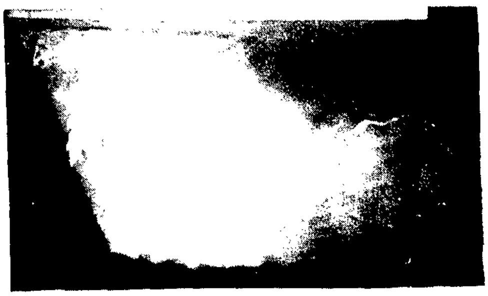
VENTILATION

-5.5°

17.5°



6.0°



21.0°

7.0°

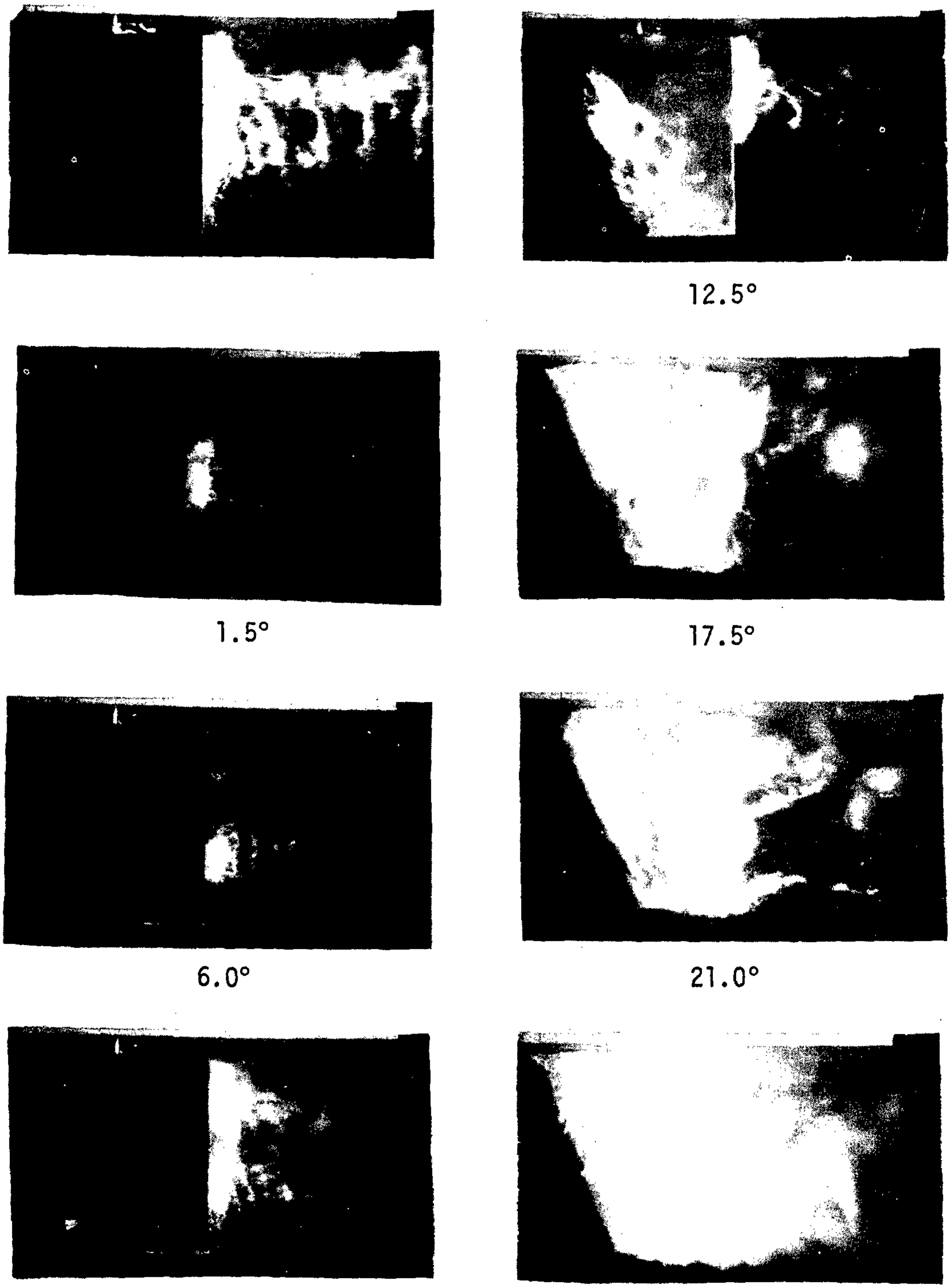
25.0°

12.5°

29.0°

Figure 18 - Condition II Corresponding to 40 Knots Full Scale

VENTILATION



12.5°

1.5° 17.5°

6.0° 21.0°

7.0° 25.0°

Figure 19 - Condition II Corresponding to 50 Knots Full Scale

VENTILATION

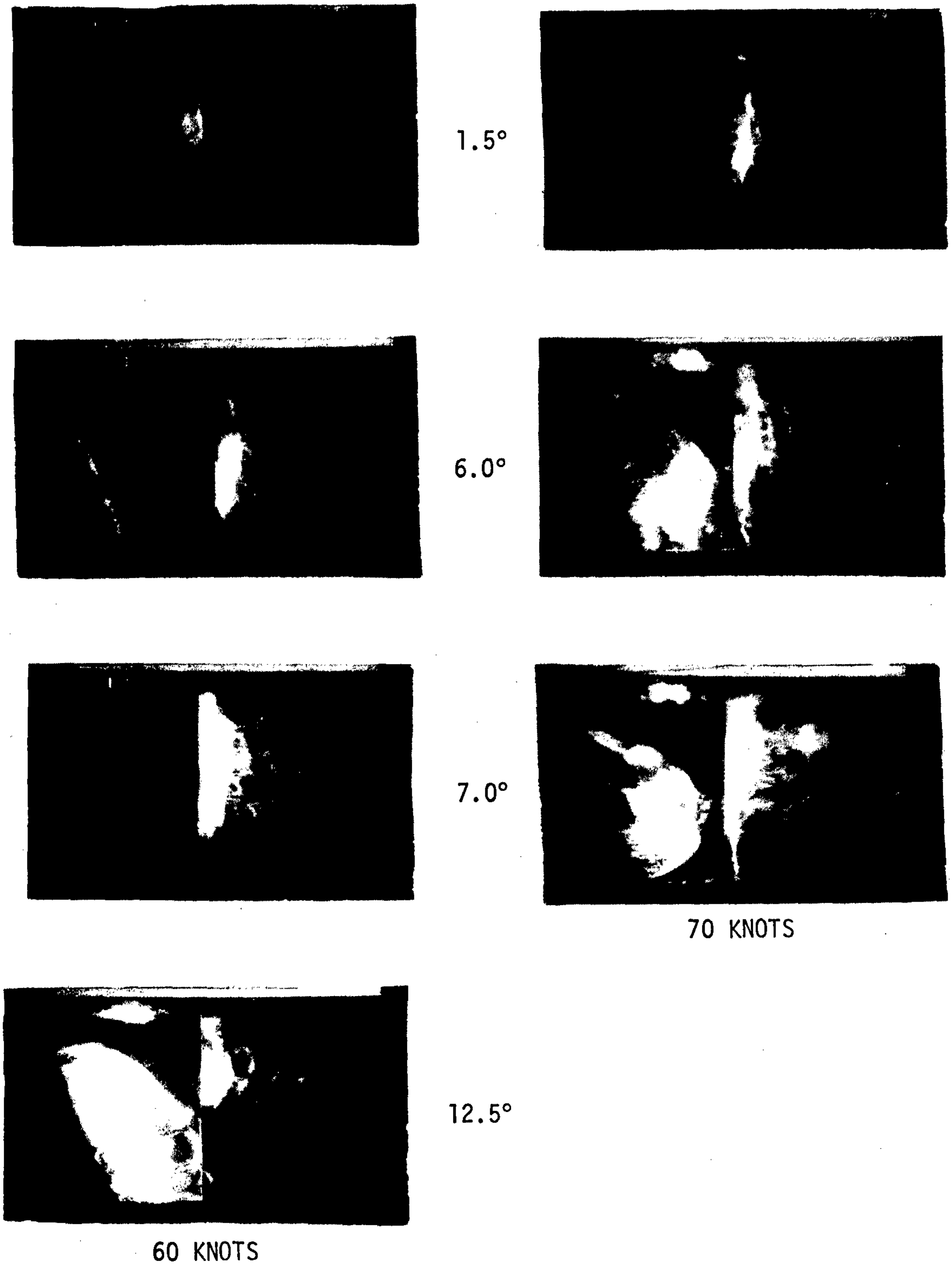


Figure 20 - Condition II Corresponding to 60 and 70 Knots Full Scale

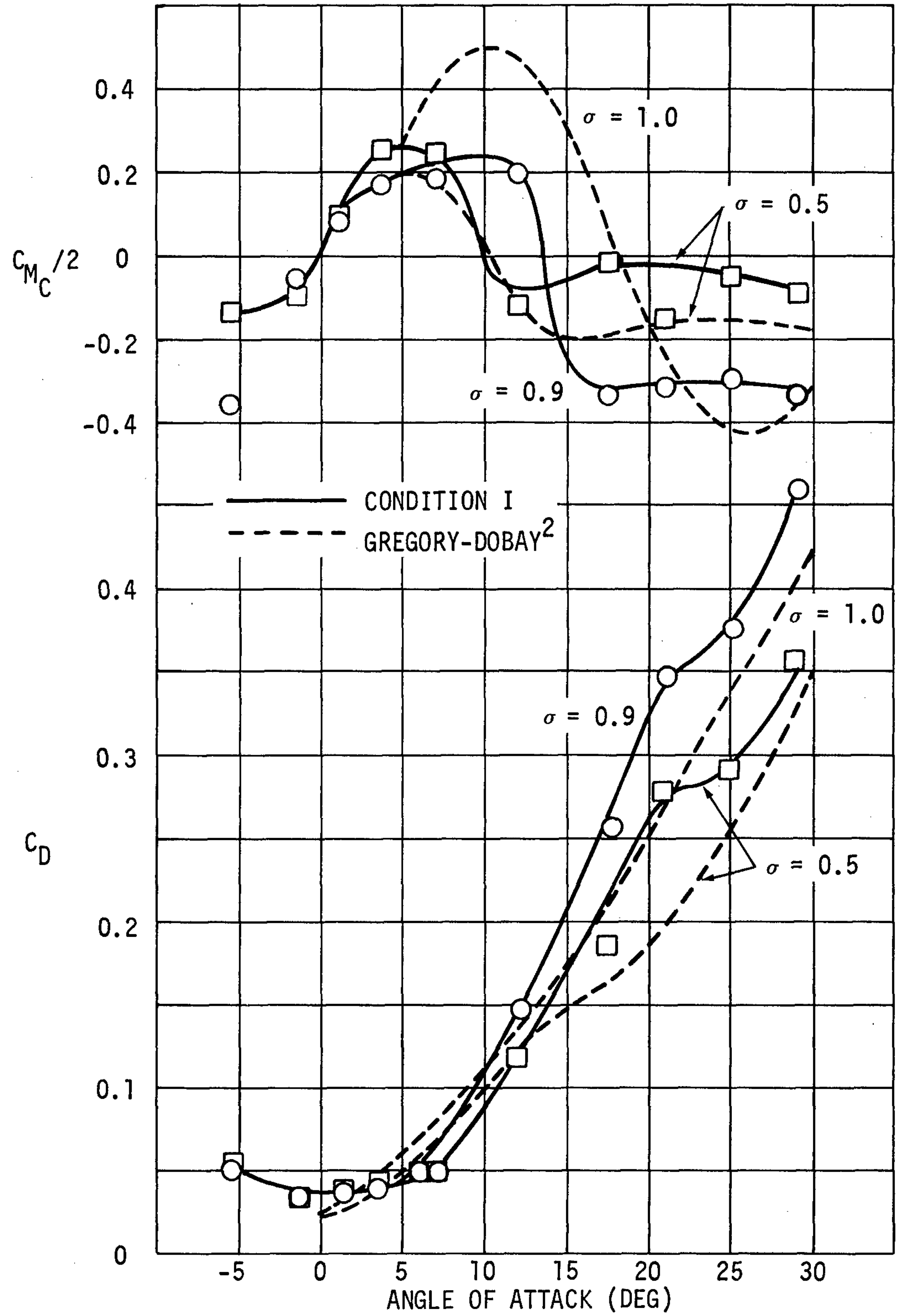


Figure 21 - Comparison of Torque and Drag Curves for Condition I and Data from Another Investigation

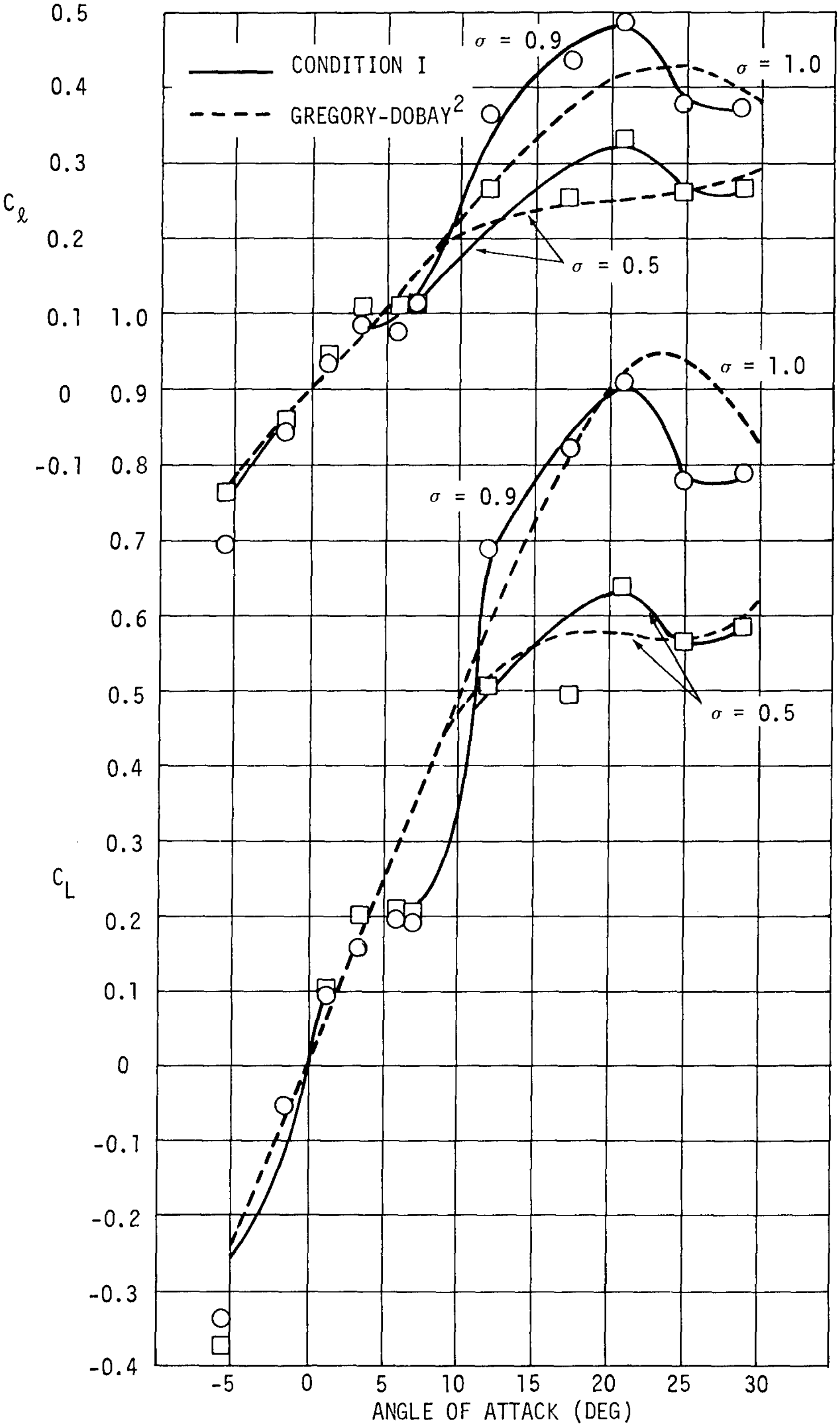


Figure 22 - Comparison of Bending Moment and Lift Curves for Condition I and Data from Another Investigation

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54	DDC
55	DDC
56	LC/SCI & TECH DIV
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58	MMA/MARITIME RES CEN
59	DOT LIB
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61	U CAL BERKELEY/DEPT NAME
62	U CAL NAME/PAULLING
63	U CAL NAME/WEBSTER
64	U CAL NAME/WEHAUSEN
65	U CAL SCRIPPS LIB
66	CIT AERO LIB
67	CIT/ACOSTA
68	CIT/WU
69	CATHOLIC U/HELLER
70	COLORADO STATE U ENGR RES CEN
71	CORNELL U/SEARS
72	FLORIDA ATLANTIC U OE LIB
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74	U IOWA INST HYDR RES LIB
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76	U IOWA IHR/LANDWEBER
77	LEHIGH U FRITZ ENGR LAB LIB
78	U MICHIGAN NAME/OGILVIE
79	MIT OCEAN ENGR LIB
80	MIT OCEAN ENGR/ABKOWITZ
81	MIT OCEAN ENGR/MANDEL
82	MIT OCEAN ENGR/NEWMAN
83	U MICHIGAN NAME LIB
84	U MICHIGAN NAME/COUCH
85	U MICHIGAN NAME/HAMMITT
86	U MICHIGAN NAME/OGILVIE
87	U MICHIGAN WILLOW RUN LABS
88	U MINNESOTA SAFHL/KILLEN
89	U MINNESOTA SAFHL/SCHIEBE
90	U MINNESOTA SAFHL/SONG
91	U MINNESOTA SAFHL/WETZEL
92	NOTRE DAME ENGR LIB
93	NOTRE DAME/STRANDHAGEN
94	PENN STATE U ARL LIB
95	SWRI APPLIED MECH REVIEW
96	SWRI/ABRAMSON
97	STANFORD U CIV ENGR LIB
98	STANFORD U/STREET
99	STANFORD RES INST LIB
100	SIT DAVIDSON LAB LIB

SERIAL	
101	SIT DAVIDSON LAB/BRESLIN
102	SIT DAVIDSON LAB/TSAKONAS
103	U WASHINGTON APL LIB
104	WEBB INST/LEWIS
105	WEBB INST/WARD
106	WHOI OCEAN ENGR DEPT
107	SNAME
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110	BOLT BERANEK AND NEWMAN LIB
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113	GEN DYN ELEC BOAT/BOATWRIGHT
114	GIBBS & COX
115	HYDRONAUTICS LIB
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117	LOCKHEED M&S/WAID
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119	NIELSEN ENGR/SPANGLER
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13. ABSTRACT

Force and moment measurements were obtained in the NSRDC 36-in. variable-pressure water tunnel on a high-speed rudder with a geometric aspect ratio of 1.47. Data presented adhere to Froude scaling with an attempt to scale appropriate cavitation number. The cavitation index was varied from 3.4 to 0.16 for angles of attack of 0 to 29 deg. Lift, drag, and rudder stock torque were all significantly affected by variations in the cavitation number. Additional data are presented for Froude scaling only without considering the effect of cavitation number. The report also indicates a decrease in forces and moments with ventilation of the rudder at the trailing edge versus no ventilation.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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1/4-Scale SES Rudder						
Froude and Cavitation Scaling						
Fround Scaling Only						